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SLOPE ANALYSIS FOR EXPLOSIVE EXCAVATIONS

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KEY WORDS: Soil mechanics, rock mechanics, slope stability, explosive excavation, strain-softening, progressive failure, stresses, strains, finite elements.

ABSTRACT: The assessment of crater slope stability requires specific information on crater geometry, geologic conditions, and material properties at the site, including seepage and weathering characteristics of the materials.

Fallback from dry rock media will behave as cohesionless material and may be studied by methods developed for the stability of rubble, talus, and rockfill. Factors of safety for the fallback portion of a crater slope should range between 1.1 and 1.5, and the rupture zone is buttressed by the fallback.

Rupture zone materials in rock would most likely fail along surfaces of natural or blast-induced fractures if the strength of the intact rock is significantly larger than the frictional resistance to sliding along the fractures. The effects on slope stability of possible long-term changes in strength and seepage characteristics in response to weathering agents are hard to assess.

The methods of analysis of explosive excavations are continuing to improve. Limit equilibrium techniques are satisfactory for design, but the continuum mechanics techniques are helpful in the research of rock behavior.

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INTRODUCTION

The term "explosive excavation" is a general term which in most instances implies "cratering" or the use of large explosive charges to produce an excavation by fracturing and ejecting large volumes of soil or rock (15, 16)². Fig. 1 illustrates a channel explosively excavated on the shore of Fort Peck Reservoir, Montana. As a rule of thumb, it is convenient to think of explosive excavation by chemical explosions in terms of tens of tons of explosives emplaced tens of feet in depth.

Explosive excavation must be cost-competitive to become an accepted method of excavation. As shown in Fig. 2, actual explosive excavation costs have been reduced. Based on the usable cross section, the cost for rock excavation is about \$2.00 per cu yd, with many additional economies still possible.

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²Numerals in parentheses refer to corresponding items in Appendix—References.

FIG. 1.— EXPLOSIVELY EXCAVATED CHANNEL, FORT PECK
RESERVOIR, MONTANA

A general understanding of the effects of a cratering explosion on the surrounding medium and of the nature of the various crater zones which are produced has been developed. Cratering experiments by both nuclear and chemical explosives and a typical slope analysis are discussed in Ref. 11.

INITIAL STEPS OF ANALYSIS

Classification of Media.— As in any slope stability analysis, the first step is the collection of site data. Primary considerations for classification are the ease and the expense involved in obtaining the

FIG. 2.— COMPARISON OF CONVENTIONAL AND
EXPLOSIVE EXCAVATION COSTS

necessary data to describe adequately the material for the intended purpose.

The media must initially be classified as to whether it is common or rock excavation in accordance with Corp of Engineers Guide Specifications. One type of material, clay shale, has been set apart as a separate entity in a system development (16). This refinement results largely from the extensive studies and experiments conducted in clay shale (12, 24).

Prediction of Crater Geometry.— When explosives are placed at a depth which gives a maximum volume of excavation, a crater is

FIG. 3.— CROSS SECTION OF TYPICAL CRATER IN ROCK, SHOWING ZONES OF DISTURBANCE

produced with relatively predictable characteristics. Fig. 3 is a typical cross section of such a crater showing crater nomenclature. This figure could be considered a cross section of a rcw crater formed by a series of single detonations or a cross section of one such detonation. Empirical formulas have been developed that correlate crater dimensions with the magnitude of the explosive charge. The apparent, or visible, crater outlines material which may be classified into three categories: the rubble zone made up of fallback and ejecta, the rupture zone, and the intact zone. The geometry of each zone is as shown in Fig. 3.

A numerical technique has been developed by Terhune (25) to predict crater geometry in lieu of scaling from past explosions. This

technique uses a digital computer to integrate the conservation laws of mass, momentum, and energy. It involves replacing the continuous spatial distribution of stress, density, velocity, etc., with a distribution defined over a grid of discrete positions (zones) in the medium. The calculations are simplified by assuming a degree of symmetry.

Two computer codes are currently used for cratering calculations. One was developed for a spherical, one-coordinate model which integrates the conservation equations written in spherical symmetry with only a radial direction of motion permitted. Another code was developed to study cylindrically symmetrical problems, such as a crater where two spatial variables are required.

At a given time, the stress, the density, the coordinates, and the particle velocity of each zone are known. The conservation-of-momentum equation provides a relationship between the applied stress field and the resulting acceleration of each zone in the grid. Accelerations acting over a small time increment produce new velocities, velocities produce displacements, displacements produce strains, and strains produce a new stress field. Time is incremented and the cycle is repeated until the mound is in freefall.

The slopes of such excavations are formed by the natural deposition of rubble after the detonation. In the creation of a row excavation, as would be needed for a canal, these slopes might be subjected once again to a dynamic loading. In some areas they would be subjected to earthquake loading. The possibility of a change to this crater geometry was studied empirically at the Nevada Test Site. Data were obtained from measurements of the effects of the seismic motions generated by the HANDLEY Event on the CABRIOLET and

SCHOONER craters (22). Accelerometers recorded the ground motions; aerial photographs and ground surveys documented the permanent ground displacements. The slopes at CABRIOLET and SCHOONER were subjected to an estimated peak radial (horizontal) acceleration of 0.74 and 0.36 g, respectively.

The analysis showed that the mode of failure of cohesionless materials, surface raveling and sloughing, did occur during the HANDLEY Event. However, the mode of failure should not be confused with a project failure, which is a mass movement of material that results in a loss of time, money, or life. Since no major changes in crater geometry occurred under severe ground acceleration, it thus appears that crater slopes are likely to remain essentially stable when subjected to large seismic motions as long as discontinuities do not cause instability in the rupture or intact zones.

Estimation of Crater Zone Stability Properties (9).— In addition to crater geometry, an analysis of crater stability requires a knowledge of the post-detonation physical and structural properties of the medium and the impact of such external factors as seepage, weathering, and seismic loading. The post-detonation properties are predicted from pre-detonation investigations of the undisturbed medium. The principles of soil mechanics are used to evaluate the properties of the rubble zone, and the principles of rock mechanics are used to evaluate the intact and rupture zones.

The material comprising the fallback and ejecta has been fractured by the explosion, broken into particles of various sizes, lifted into the air or sloughed down, and redeposited in a somewhat predictable pattern. This is crater rubble. If the detonation is in rock, the

rubble is more or less loose blocks of material, the faces of which are preexisting discontinuities or blast-induced fractures. The strength analysis of the rubble zone is primarily an assessment of the stability of cohesionless rubble slopes. The factor of safety for dumped large aggregate, a situation roughly analogous to the formation of crater slopes, normally varies between 1.1 and 1.5 (20).

For other than very weak rocks, the strength of the rock mass in the rupture zone is governed by the spacing and orientation of the natural and blast-induced fractures; therefore, careful site documentation is necessary. The materials near the crater have been highly fractured by the explosion. In the rupture zone natural discontinuities are disrupted and large subsurface displacements are common (10).

Exploratory drilling in the rupture zone below the preshot ground surface has provided information on the increase in the intensity of fracturing. In the portion of the rupture zone near the true crater boundary, fracturing increases in intensity by several hundred percent as compared to the preshot in situ fracturing (Fig. 4). The majority of blast-induced fractures are alined in a direction nearly parallel to natural fractures. The effective porosity (volume of continuous voids/total volume) of the materials in the rupture zone is increased significantly as a result of the cratering detonation. This increase is due primarily to the opening of both natural and blast-induced fractures. Investigations of several craters in basalt, having a preshot effective porosity of approximately 2%, have indicated blast-induced porosities of as much as 25% near the true crater boundary (10). Fig. 4 schematically illustrates the decrease in blast-induced fracturing and effective porosity with distance from the true crater boundary.

FIG. 4. — REPRESENTATIVE VALUES OF BLAST-INDUCED FRACTURING AND INCREASED POROSITY IN RUPTURE ZONE

For explosively excavated craters in rock the permeability will generally be high because of the fracturing and the material will drain easily; thus the stability of such slopes will not be affected to any great extent by seepage pressures (23).

METHODS OF ANALYSIS

Empirical Analysis. — In the empirical approach, a prediction of the performance of a crater slope is based largely upon empirical data relative to the observed performance and characteristics of comparable man-made or natural slopes. To use the empirical approach, sufficient site information must be collected so that the

material in which an excavation is planned may be characterized for comparison with observations and data which have been previously gathered and catalogued in other locations. The primary advantage of this approach is that it can circumvent a lack of detailed site data and crater slope properties. Several reports deal with this method of analysis for crater slopes (12, 17, 19, 24). Don C. Banks is presenting results from Refs. 12 and 24 at this meeting.

Limit Equilibrium Analysis.— This section discusses four limit equilibrium methods: (a) the method of slices for circular slip surfaces, (b) the method of slices for composite failure surfaces, (c) the method of wedges, and (d) the method of three-dimensional wedge analysis. These methods can account for the effects of pore water pressure, seismic loadings, and long-term strength losses on the stability of a crater slope. The methods presented are two- and three-dimensional limit equilibrium analyses applicable to linear row craters of semi-infinite extent. Ref. 3 applies the first three methods to explosive excavations, and Ref. 14 presents an excellent evaluation of the fourth.

The first three methods are considered to be most applicable to those portions of a crater slope in which the slope materials behave as masses of angular, aggregated particles such as exist in the rubble zone of a crater (Fig. 3). Three-dimensional solutions for cases in which structural discontinuities may play an important role, such as in the rupture and intact zones of crater slopes in rock, are handled by the fourth method. When the fractured and intact zones behave in a two-dimensional manner, all four methods are applicable. This condition may exist when joints, fractures, and other discontinuities have strike directions which parallel the center line of the excavation

or when discontinuities are randomly oriented but have such a close spacing that the mass behavior is similar to that of a relatively homogeneous material. Limit equilibrium methods of analysis have recently been developed to analyze problems in three dimensions which are explained and illustrated in Ref. 14. In rock slopes the potential system of failure surfaces already exist in the mass, but the kinematics of sliding must be checked to delineate the possible directions and surfaces on which it is physically possible for sliding to take place.

The following is an example of a two-dimensional wedge analysis. Its purpose was to evaluate whether fallback provides a buttressing effect against failure in the rupture and intact zones and to quantify the improved factor of safety. The type of failure analyzed was that of a wedge slide with the strike of the plane of sliding parallel to the slope and "daylighting" into the true crater.

The geometric configuration of the crater for analysis is shown in Fig. 5. All surfaces are considered planes. The cross section of the apparent crater has been approximated by two straight lines.

The failure surface was defined by the parameters α , β and H (Fig. 5). For each value of H , a factor of safety was calculated for various values of α and β .

The side forces between blocks are also shown in Fig. 5. The force acting between blocks 1 and 2 is denoted E_{12} and was assumed to act horizontally. E_{12} is a maximum value and is found by varying the angle η until a maximum value of E_{12} is reached.

The side force E_{23} between blocks 2 and 3 was assumed to act at an angle parallel to the line above it approximating the apparent crater. The value of E_{23} is a function of the parameter α and the weight of the wedge determined by α .

FIG. 5.— CRATER MODEL FOR LIMIT EQUILIBRIUM ANALYSIS

When the failure surface does not daylight in the crater, two passive blocks exist. The side force E_{34} was assumed to act horizontally on the boundary and can be found by the Rankine equation for a passive wedge.

For each failure surface the factor of safety was calculated for two conditions, one with fallback and one with no fallback. The analysis showed that the presence of fallback in an explosively produced crater will increase the stability of a plane of weakness in the rupture zone. The amount of increase is dependent on the dip and depth of the failure plane and the strength of the material along the plane. An increase of over 100% in the factor of safety (0.56 to 1.25) has been computed for $H = 80$ ft and $\beta = 45^\circ$ with the angle of internal friction along the plane of weakness equal to 30° .

Although this example was calculated to analyze the influence of fallback in slope stability, it can also be used as a tool for analyzing the stability of particular slopes. Planned craters through geologic media containing known and mapped planes of weakness can be analyzed to determine the best line of construction. The case of no fallback is similar to that of an open pit mine, and the case with fallback is similar to talus slopes.

Continuum Mechanics Analysis.— In order to make a stability analysis that avoids the upper-bound theory of limit equilibrium analysis, some form of stress analysis of the continuum is required. This stress analysis will provide the information necessary to make a stability analysis; i.e., to find the factor of safety.

Numerical or experimental methods might be used for the stress analysis. Of the numerical methods, the finite difference and the finite element methods are the most popular. Because the finite element method has been used extensively in the study of crater slope stability, this section will deal only with that method of numerical stress analysis. The finite element method, as discussed here, is a displacement method of analysis and the discussion is restricted to plane strain. Further, the emphasis will be placed on the mathematical model to represent the soil or rock.

There are limitations to the use of the finite element method. The primary limitation is the inability to determine accurately and to describe the actual complex properties of the intact rock material and the rock mass. Another limitation is the inability to model completely the inelastic behavior of rock during the loading through failure. Both of these limitations are recognized; however, many efforts in rock

mechanics are directed toward improving the capabilities of the finite element method.

In the past few years the Corps of Engineers has funded many studies of the use of the finite element method for slope stability analyses (6, 7, 8, 18). The major variations studied are boundary conditions (slope angle, initial stress conditions, and methods of loading) and material properties (modulus of elasticity, Poisson's ratio, cohesion, angle of internal friction, and unit weight). The finite element method is very versatile and can be used with different methods of modeling the stress-strain patterns of earth materials.

Some Results of Parameter Studies with Finite Element Method. — The initial state of stress at a location and the method of its application to a cut slope have been found to be most important. The initial state of stress should be applied directly to the elements at the beginning of the analysis for the most direct and probably the most realistic analysis. The vertical stress should be taken as the overburden stress, and the horizontal stress should be taken as proportional to this overburden stress with the constant of proportionality being K , the coefficient of earth pressure at rest. The value of K can be greater or less than one depending on the geologic history of the location; i.e., it need not be the value derived from elastic theory. Values less than one can be associated with normally consolidated clays and values greater than one with overconsolidated clays. The authors of both Refs. 6 and 7 found that the stresses at the toe of a slope are greater for higher values of K and the factor of safety is lower, particularly against progressive failure.

Although explosive excavations create slopes "instantly," incremental unloading or excavation is required for inelastic analyses.

This is the approach taken for the explosive excavation studied by Palmerton and Banks (21) in which horizontal layers were removed from the semi-infinite mass to create a slope modeling an explosive excavation.

In addition to the obvious relations for slope angle, cohesion, and angle of internal friction with stability, it has been pointed out by Kulhawy et al. (18) that if the technique requires a fixed Poisson's ratio, higher values of Poisson's ratio will give higher factors of safety. This relationship could be misleading. This role of Poisson's ratio is unfortunate, since it is seldom measured on intact samples and must be assumed for a rock mass. It is suggested that analyses either use a technique that modifies Poisson's ratio internally such as the method presented in Ref. 18 or several runs be made with different estimates of Poisson's ratio.

The factor of safety along assumed failure surfaces can be computed with the stresses from the finite element method; however, care should be taken to insure that the definition is consistent for both finite element and limit equilibrium analyses. When the factor of safety is defined with respect to the value of shear stress for a potential failure surface, its value from a finite element analysis is very close to that calculated by means of the best limit equilibrium analysis procedures (18).

One limitation of the finite element method was removed by Duncan and Goodman (8) when jointed rock properties were introduced into the model. Although the discontinuities would have to be fixed before the analysis was made, this limitation is satisfactory if geologic investigations have found predominate joint patterns or a particularly significant discontinuity.

Although the mathematical models to represent the stress-strain behavior of earth materials are discussed in the next section, one property of a particular model should be pointed out at this time. As mentioned above, the value selected for Poisson's ratio plays an important role in the factor of safety calculated. The inelastic technique presented by Kulhawy et al. (18) not only allowed the stress-strain curve to be simulated by a hyperbola, but also the axial strain-radial strain curve. This improvement removes the requirement to assume a value of Poisson's ratio and includes volume change characteristics.

Mathematical Models to Represent Stress-Strain Behavior of Earth Materials.— Only the imagination of the engineer limits the possible mathematical models that can be used to represent the stress-strain behavior of earth material. Although the models that have been used in connection with rock slope stability are somewhat limited, there are many models used by researchers modeling earth material to evaluate the effect on structures of ground shock from a large explosion. Some of the more sophisticated and recent are reported in Refs. 2, 4, and 5, with Ref. 4 reviewing several models.

The material properties to be modeled must be determined by extensive testing. The stress-strain curve and the shear strength envelope are frequently referred to as the constitutive equations. When Hugoniot data (measures of material compressibility as a function of very high applied loads) are also developed for the rock through its various modes of material behavior (gas, liquid, solid), the test results are called the equation-of-state. This information is particularly important when the material response from nuclear excavations (25) is modeled.

The simplest model for slope stability is the elastic assumption. Refs. 6 and 7 used this model primarily. The fact that incremental loading is not required for the elastic assumption results in a considerable saving of computer time. Although the stresses and factors of safety from this method are compatible with limit equilibrium methods, efforts continue to improve modeling of the inelastic behavior of the material.

The author (13) considered four models for the stress-strain curve, one being the elastic, two being variations of stable inelastic, and the fourth being unstable inelastic. Baker et al. (1) also applied one of the stable inelastic models to slope stability analysis. Kulhawy et al. (18) considered one stable inelastic model in addition to the elastic model.

Fig. 6 illustrates six models of stress-strain curves. All can be made to fit test results with varying degrees of accuracy. The models illustrated in Figs. 6(b), 6(c), 6(e), and 6(f) use a generalized Mises criterion. The parameters needed for this yield condition are cohesion and angle of internal friction. The hyperbolic stress-strain curve of Fig. 6(d) was first used on slopes by Kulhawy et al. (18). Three constants taken from the sample stress-strain curve to be modeled are required for this model. An additional output from these inelastic analyses is a zone in the slope that has yielded or failed. Only Palmerton and Banks (21) have applied one of these inelastic models to an explosively excavated slope. Both Kulhawy et al. (18) and Palmerton and Banks (21) applied the hyperbolic stress-strain model to the Otto Brook dam and calculated the displacements within good tolerance with the actual displacements.

(a) Elastic

(b) Elastic-plastic

(c) Stable inelastic (bilinear-elastic then plastic)

(d) Stable inelastic (hyperbola)

(e) Progressive failure (unstable inelastic, without modification)

(f) Progressive failure (unstable inelastic, with modification)

FIG. 6. — MODEL STRESS-STRAIN CURVES

Only parameter studies of a 45° slope have been made with the models of Figs. 6(b), 6(c), 6(e), and 6(f). The model of Fig. 6(f) was developed because of an inability of the model of Fig. 6(e) to balance the equilibrium equations involved, although the latter did show the progressive growth of the failure zone. The model of Fig. 6(f) uses two straight lines to represent bilinear inelastic behavior initially. The point at which the line bends will be an initial yield point corresponding to the peak strength of the material. The same yield criterion will be used for the second yield point; however, the elastic modulus is considerably reduced, and the internal friction or cohesion is increased slightly. This second yield corresponds to the reduction in strength known as strain-softening, and the stress drops to a new yield surface represented by the residual strength, usually a considerably reduced angle of internal friction with zero cohesion. At this new stress level, the material is assumed to behave in a perfectly plastic manner. Any unloading of an element during the analysis is assumed to be elastic with no hysteresis loss, as illustrated in Fig. 6.

Example of Progressive Failure Model.— A current research project by the author applies the lessons learned and discussed in the sections above concerning the use of the finite element method. The progressive failure model of the stress-strain curve of Fig. 6(f) is used and is shown again in Fig. 7 with values from this example.

Both the initial state of stress and the incremental unloading of the slope are applied as recommended above with $K = 1.0$. The strength properties selected are representative values from Ref. 24 for Cucaracha and Culebra clay shale.

FIG. 7.— PROGRESSIVE FAILURE STRESS-STRAIN CURVE
(UNSTABLE INELASTIC, WITH MODIFICATION)

FIG. 8.— SURFACE DISPLACEMENTS AND MODIFIED AREAS OF
PROGRESSIVE FAILURE ANALYSIS

The results of this analysis are shown in Fig. 8, in which the displaced surface is illustrated schematically to show the mode of failure. The elastic model has a similar mode of failure with much smaller displacements. The modified zone and plastic zone after the last increment are also illustrated.

This example took approximately 2 hr on a CDC-3600 computer and is thus of research value rather than for production design. It will be used to evaluate further the effect of the mathematical model on the stress distribution and the factor of safety. The technique of this example is no substitute for the well-established limit equilibrium methods of soil and rock mechanics at this time, but it may lead to better understanding of the effects of progressive failure.

JUDGMENT OF STABILITY

The final step in the analysis is a judgment of the stability potential of a planned crater. The assessment is based upon an integration of the data developed by previous steps, technological experience, and engineering judgment.

At the present time, application of the analytical approach is limited by several factors. To date, experimental crater slopes have experienced no significant failures which could be used to study failure geometries and backfigure material strengths. In addition, the methods required to predict precisely the parameters required for numerical analyses are not available. Although assumed ranges of parametric values might be used in lieu of precise values, calculated safety factors are very sensitive to small changes in input parameters.

SUMMARY

The assessment of crater slope stability requires specific information about crater geometry, geologic conditions, and material properties at the site, including seepage and weathering characteristics of the materials.

Fortunately there are certain general characteristics of craters and crater slopes that make them inherently stable. Fallback from dry rock media will behave as cohesionless material and may be studied by methods developed for the stability of rubble, talus, and rockfill. Factors of safety for the fallback portion of a crater slope should range between 1.1 and 1.5, and the rupture zone is buttressed by the fallback.

Rupture zone materials in rock would most likely fail along surfaces of natural or blast-induced fractures if the strength of the intact rock is significantly larger than the frictional resistance to sliding along the fractures. A major uncertainty in sample analysis and in the assessment of crater stability in general is the possibility of long-term changes in strength and seepage characteristics in response to weathering agents.

The methods of analysis of explosive excavations are continuing to improve. Limit equilibrium techniques are satisfactory for design, but the continuum mechanics techniques are helpful in the research of rock behavior.

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